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# Angular and Energy Dependence of Proton Upset in Optocouplers†

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## *Abstract*

Transient upsets from protons in high-speed optocouplers were investigated over a range of incident angles and energies. At energies below 50 MeV, very large increases in cross section occurred at angles above 60 º, consistent with the increase in cross section that is expected when direct proton ionization begins to contribute to the cross section. The angular dependence of the cross section increases the number of transient upsets expected in orbit compared to upset rate calculations that do not take the angular dependence into account. Laboratory alpha particle measurements were used to measure critical charge in these devices. The critical charge and area of the photodiode provide a way to identify devices that are sensitive to direct ionization at large angles.

## I. Introduction

Proton upset effects in optocouplers were reported by LaBel, et al. that showed an unexpected increase in cross section for incident angles above 80 degrees [1]. With 62 MeV protons, the cross section increased by about a factor of six. Although it appeared that the increased cross section was related to direct ionization from protons, the angular dependence was weaker than expected from basic geometrical arguments using a shallow charge collection depth. Later work showed that the angular dependence of proton upset observed in the earlier studies at a single energy could be explained by considering the distribution of proton recoil energies along with the assumption of a deeper charge collection depth, which was consistent with upset tests from heavy ions [2]. However, an experimental test of the underlying assumptions in the latter work has yet to be done.

Protons in space not only arrive over a wide range of incident angles, but also involve a distribution of proton energies. It is necessary to understand both the angular dependence and the dependence of proton upset on energy in order to determine how optocouplers will respond in space. If the angular dependence only occurs for extreme angles of incidence, it will have little impact on the overall cross section because of the narrow acceptance angle. However, if the angular dependence occurs at less extreme angles, the effect will be far more important on the net upset rate in space.

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The present work examines mechanisms for proton upset in optocouplers in more detail, investigating both the energy dependence and the effects of different load conditions on the cross section. The mechanism for the increased cross section at large angles is shown to be due to direct ionization. A laboratory screening method is developed to determine whether direct ionization is significant for specific device types.

## II. Device Construction and Operation

Type 6N134 optocouplers from two different manufacturers, Hewlett-Packard and Micropac, were used in this study. Both manufacturers use a sandwich construction, placing an assembly that contains the light-emitting diode directly over a silicon photodiode, as shown in Figure 1. The photodiode is part of an integrated circuit that contains a high-gain amplifier (of proprietary design) with an open-collector output stage. The diameter of the circular photodiode is 430 µm for the HP devices, and 460 µm for the Micropac devices (a difference in area of 15%). The physical construction of parts from the two manufacturers is similar, other than the difference in photodiode area. Although not shown in the diagram, a film of optical coupling material is placed between the LED and silicon assemblies to increase the optical coupling efficiency.

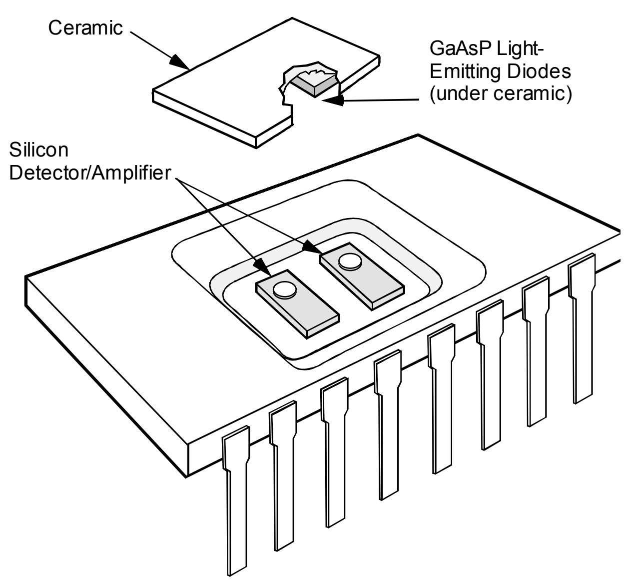



Figure 1. Physical diagram of the 6N134 optocoupler.

The 6N134 is a high-reliability device in a ceramic package. Commercial optocouplers in plastic packages use somewhat different assembly techniques, substituting a thin plastic film for the ceramic LED substrate used in the 6N134.

The minimum optical power required to switch these devices is weakly dependent on load conditions. Figure 2 shows the transfer characteristics of a typical 6N134 optocoupler -- input LED current vs. output voltage with a resistive load -- for three different load conditions. Assuming that LED output power is proportional to load current, approximately 30% more light is required to switch the device with a 4 mA load current compared to the lightly loaded 1 mA condition. As will be seen later, the difference in optical sensitivity, which is caused by the finite gain of the amplifier, also causes the SEE response threshold to be slightly different for different load conditions. A larger load resistance increases SEE sensitivity.

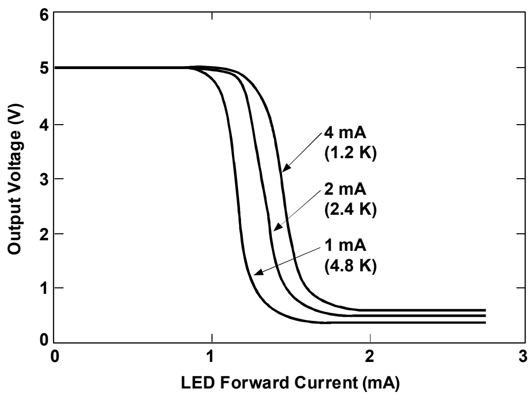



Figure 2. Output voltage vs. LED input current for three different load conditions (load resistance shown in parentheses)

## III. EXPERIMENTAL RESULTS AT ACCELERATORS

The devices were irradiated at energies of 64, 95 and 195 MeV at the Indiana University Cyclotron, and at 15, 30 and 50 MeV at the University of California Davis cyclotron. Tests at Davis were done with three different load conditions, corresponding to full-scale currents of 1, 2 and 4 mA with a 5-V power supply. The tests at Indiana University were done with only one load condition (2 mA). A high-speed digital oscilloscope was used to capture each individual waveform during each test run. Devices were placed in the “1” state (no current through the LED).

Tests at UC Davis were done on devices with the lid and the LED assembly above the silicon die removed to reduce the shielding effect of those materials, which can be an important interference at low energies. The silicon die from both vendors is recessed within the cavity of the dual-in-line ceramic package. The side of the package was ground away in order to allow low-energy protons to strike the surface of the device at large angles without first traversing the package sidewall. If this is not done, scattering from the package will affect the results, producing a distribution of protons with lower energies.

Although the output of these devices is digital for normal operation (with the LED driven well beyond the threshold conditions shown in Figure 1), tests with heavy ions or protons produce a distribution of output amplitudes, just as for single-event upset tests of analog comparators [3-7]. Thus, one must set a specific output triggering condition when measuring output transients. Figure 3 shows a sequence of fourteen output pulses from a single test run with 64 MeV protons. Many of the transients have amplitudes near the saturation level, but there are a number of pulses with reduced amplitude and pulse width.

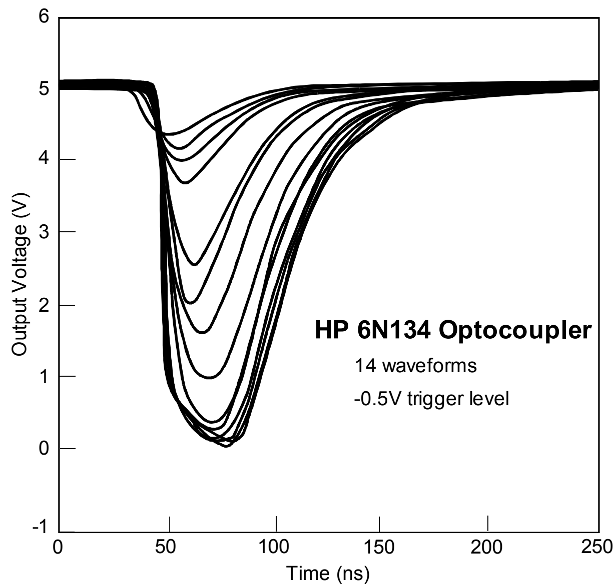



Figure 3. Sequence of output transients for a 6N134 optocoupler.

For our tests, the triggering threshold was set for 4.5 V (a -0.5 V transient signal). Cross sections were measured by counting the number of transients that occurred for this condition, but since each individual waveform was stored it was also possible to analyze the results for larger threshold triggering conditions or for other threshold criteria (such as exceeding a specified pulse width).

Tests with 195 MeV protons showed no angular dependence (the lack of angular dependence at high energy was also reported by the group at GSFC [8]). A very weak angular dependence was observed at 95 MeV, and at 64 MeV we observed an increase in cross section of about a factor of six at the maximum angle used (87.5 degrees). The latter result is identical to the results reported by LaBel, et al. in their initial study [1].

When the optocouplers were tested at energies below 60 MeV the effect of incident angle on cross section increased dramatically compared to results with higher energies. Figure 4 shows the angular dependence of the cross section for the HP 6N134 at three different proton energies. At 50 MeV the cross section increases by nearly an order of magnitude compared to the cross section at normal incidence. The angular dependence begins to become significant at about 75 º. At lower energies the angular dependence begins at smaller angles, and the cross section increases by large factors at high angles. The cross section is more than three orders of magnitude higher at large angles with 15 MeV protons compared to the cross section at normal incidence!

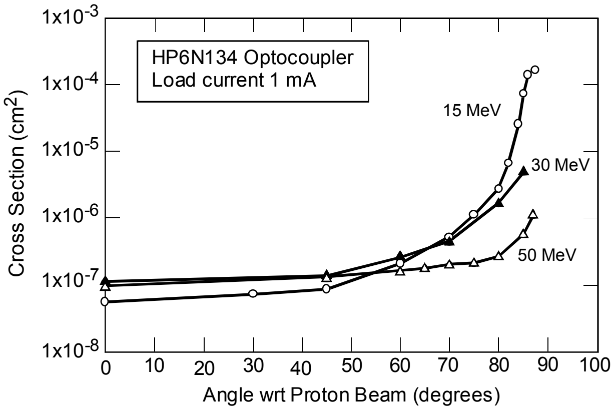



Figure 4. Effect of incident angle on cross section of the HP 6N134 optocoupler for various proton energies

The 6N134 from Micropac also exhibited a strong dependence on angle of incidence. These results are shown in Figure 5; the results are very similar to the results for the HP version of the part. However, for the Micropac device the maximum cross section at 15 MeV is nearly an order of magnitude lower than that of the HP version of the part. The cross section of the Micropac devices appears to level off at an angle of approximately 85º. That same trend is evident in the HP part as well (see the previous figure), but is not as obvious because of the more extreme angular dependence of the HP device.

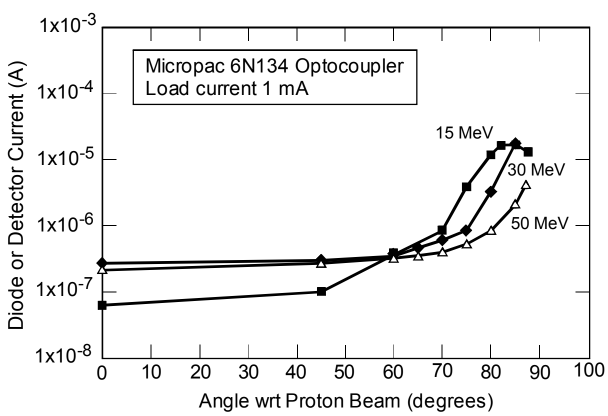



Figure 5. Effect of incident angle on cross section of the Micropac 6N134 optocoupler for various proton energies.

The effect of different load conditions on the angular dependence of the cross section is shown in Figure 6 for the HP 6N134 optocoupler. When tested with a 4 mA load, somewhat higher angles were required in order for the angular dependence to occur. The maximum cross section was also slightly lower for the higher load condition.

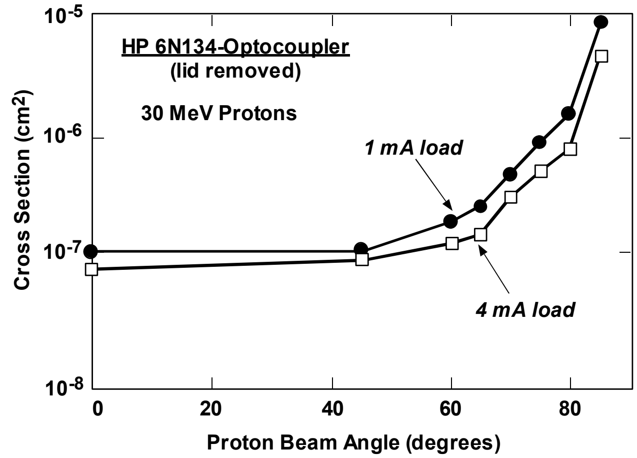



Figure 6. Effect of different load conditions on the angular dependence of the cross section of the HP 6N134 optocoupler with 30 MeV protons.

## IV. Alpha Particle Experiments

A series of experiments was done with laboratory alpha particle sources to determine critical charge. Thin gold foils were interposed between the source and the optocoupler to degrade the alpha particle energy. The energy of the degraded particles was calibrated by measurements with a surface-barrier detector. This approach allows us to effectively use several different alpha particle energy values to test the optocouplers. We measured the amplitude and pulse width of the optocoupler transients at various energies. Three different loading conditions were used for the critical charge measurements: full-scale load conditions of 1, 2 and 4 mA.

Alpha particles strike the photodetector at random locations, and "hits" near the periphery produce smaller transients than those that pass through the main region of the detector. Thus, we have to deal with a distribution of output amplitudes for each experimental condition. Figure 7 shows how the mean amplitude varied with alpha particle energy (more than 100 waveforms were collected for each run). For high alpha energies, most of the waveforms produce a full (saturated) output voltage, but as the energy was reduced, the mean amplitude decreased. We used the condition where the mean amplitude decreased to 1/2 of full scale (in this case 2.5 V) to calculate critical charge. Note, however, that the dependence of mean amplitude on energy is very steep in this region, so that the critical charge is only slightly lower if a lower mean amplitude criterion is used.

The cross section decreases somewhat with lower energy alpha particles. At the threshold condition, the cross section is about 75% of the physical area of the photodiode. With higher alpha energies, the cross section is about 50% greater than the physical area of the photodiode. This is consistent with the earlier results with heavy ions that showed a steady increase in cross section with LET near threshold conditions [2]; the changing cross section is consistent with the observation that charge collected by diffusion is a significant fraction of the total charge that "drives" the amplifier.

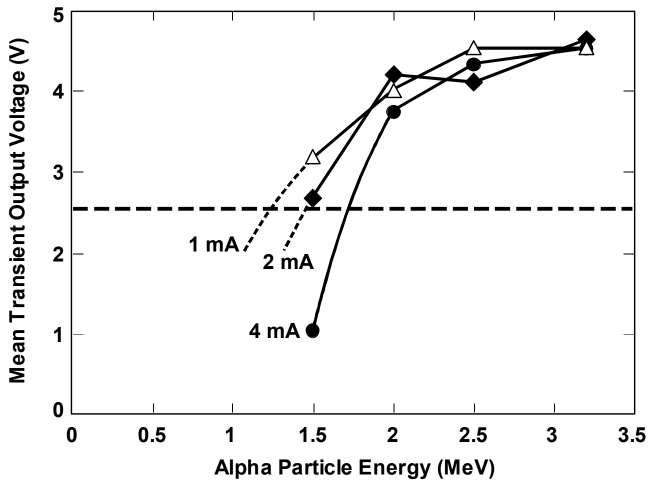



Figure 7. Determination of critical charge from laboratory alpha particle irradiations.

Critical charge determined from the alpha particle experiments is shown in Figure 8. For the Hewlett-Packard device, it varied between 0.055 (1 mA load) and 0.076 pC (4 mA load). The ratio of the critical charge is essentially the same as the ratio of the LED threshold current for those two load conditions in normal (electrical) operation; see Figure 1. The critical charge for the Micropac devices was about 30% higher than that of the HP devices.

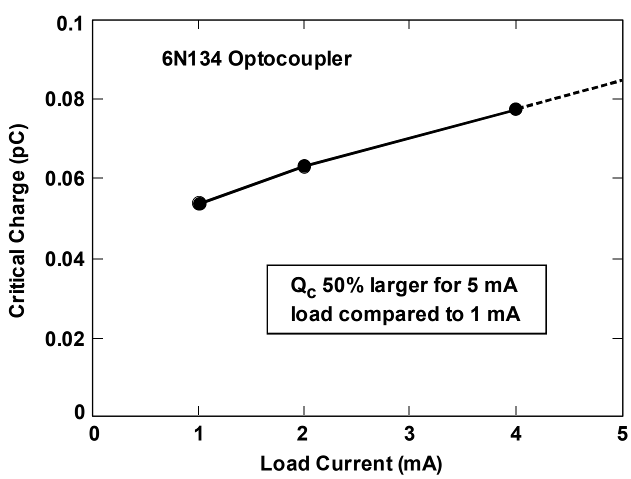



Figure 8. Critical charge for different load conditions

Low-energy alpha particles have very short range, and the accuracy of critical charge measurements can be affected by absorption of some of the incident alpha particle energy in passive coating material on the optocouplers. There is also an index-matching compound that is placed between the LED assembly and the silicon die. The index matching material must be removed with a solvent before doing the alpha experiments, because it can be up to 100 µm thick.

In order to reduce surface reflection, the thickness of the optical coating is approximately 1/4 the wavelength of the light, or about 0.2 µm. This introduces an error of less than 10% in the critical charge.

The critical charge measurements with alpha particles (at normal incidence) are in close agreement with the proton test results at high angles of incidence for different load conditions. For example, the ratio of the secant of the angles at which the cross section increases with 1 and 4 mA load conditions in Figure 4 is 1.30, nearly the same ratio as the critical charge for the two load conditions from alpha particle measurements in Figure 7 (1.34). This provides an additional check on the effect of energy loss in overlayers in the alpha experiments. If significant energy losses occurred, then the critical charge from low-energy alpha particle measurements would have a different ratio for different load conditions than experimental measurements with high-energy protons, which have much longer range, and are essentially unaffected by energy absorption in the overlayer.

Only certain types of optocouplers are affected by proton upset. It is possible to do a first-order calculation to determine whether direct ionization effects are important by combining laboratory measurements of critical charge using alpha particle sources with the dimension of the photodiode. The maximum charge at extreme angles is simply the product of the LET of protons at various energies and the diameter of the photodiode, as supported by the data at different energies and load conditions. For most spacecraft, sufficient shielding is present so that the number of protons below approximately 5 MeV falls off sharply. Thus, 10 MeV will be used as an arbitrary criterion for first-order calculations to determine whether proton upset at extreme angles is likely to be important.

For the 6N134, the critical charge with a 1 mA load is 0.05 to 0.07 pC (it differs for the two manufacturers). The LET of a 10-MeV alpha particle is $3.2 \times 10^{-2}$ MeV-cm$^2$/mg *[$3.3 \times 10^{-4}$ pC/µm]*. Thus, a total charge of 0.14 pC will be generated in a path length of 430 µm (the diode diameter), which is well above the critical charge. Therefore, direct ionization is expected to be a significant issue for the 6N134 optocoupler. Although this is far from an exact model of proton upset, it provides a convenient, low-cost method to determine whether more complete tests at various proton energies and angles are necessary to characterize a specific device.

## V. Discussion

### *A. Range and LET of Protons with Various Energies*

Two factors are involved in the proton energy dependence: the distribution of recoil energies from proton reactions (see references 9 and 10), and the linear energy transfer of the protons (direct ionization). Table 1 shows the LET of various proton energies. The LET varies by about a factor of five over the range of proton energies that were used in our experiments, increasing at low energies.

Table 1. LET and Range of Protons

| Energy (MeV) | LET (MeV-cm2/mg) | LET ratio (compared to 65 MeV) | Range in Si (µm) |
|---|---|---|---|
| 15 | 0.024 | 3.00 | 1,585 |
| 20 | 0.020 | 2.50 | 2,580 |
| 30 | 0.015 | 1.88 | 5,220 |
| 50 | 0.010 | 1.25 | 8,610 |
| 65 | 0.008 | 1 | 18,000 |
| 100 | 0.0064 | 0.80 | >20,000 |
| 195 | 0.0041 | 0.51 | >20,000 |

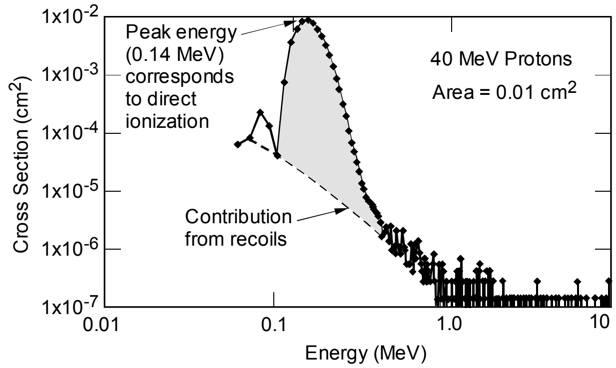



Figure 9. Charged particle measurements of a 50 µm surface barrier detector using a tagged measurement procedure with 40 MeV protons.

At high energy, the LET is lower but the distribution of recoil energies is higher. Both mechanisms are potentially important in these optocouplers because of the very low critical charge. For high-energy protons, recoil products can cause upsets to occur, whereas at low energies direct ionization is likely to be the dominant mechanism. It is possible for both mechanisms to contribute to upset at intermediate energies, and that is one of the main challenges in developing models for SEE effects in these structures.

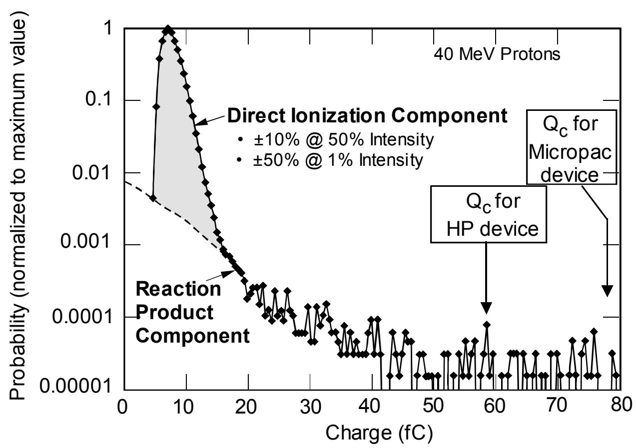
## *B. Spectra of Proton Reaction Products*

Although proton recoil spectra have been published in the past [9,10], signal-to-noise limits the accuracy with which such spectra can be determined with standard counting methods. A special approach, using "tagged" protons, was used to make proton recoil spectra measurements at the University of Indiana (results from a similar set of "tagged" proton experiments were reported last year using semiconductor devices as charge-sensitive detectors [11]). Our experiments were made on a surface barrier detector with a 50 µm thickness, which is nearly identical to the effective charge collection depth of the 6N134 [2]. Thus, the charged particle spectra from the detector are expected to be nearly identical to the energy distribution within the photodiode of the 6N134 at normal incidence.

Figure 9 shows an example of the measured particle spectrum of the surface barrier detector with 40 MeV protons. Note the peak at low energies which corresponds to direct ionization across the 50 µm region. This peak has a finite width, which is caused by statistical fluctuations in the angle and charge state of the protons when they lose energy to the silicon lattice via ionization (energy straggling). The measurement combines the effects of direct ionization (with straggling) along with the charge generated from reaction products. The dashed line shows how the reaction product spectrum continues in the region where direct ionization dominates.

The results of Figure 9 have been redrawn in Figure 10 to show the relative probability of occurrence vs. collected charge for the 50 µm surface barrier detector. The critical charge for optocouplers from the two manufacturers are also shown in the figure. Two points should be noted: first, at 40 MeV the direct ionization peak is far below the critical charge for either device; and second, when the experiment on the *optocoupler* is done using protons at other than normal incidence only the direct ionization component will be affected by angle. To first order (as long as the lateral dimensions are much longer than the mean path length of the recoil products), the recoil contribution depends on volume, and is not expected to vary with incident angle. Only the ionization peak is angle dependent, and therefore the increase in cross section with angle has to be due to direct ionization.

Figure 10. Results of figure 9 plotted to show the distribution of collected charge.




The finite width of the ionization peak is of critical importance in the cross section because the "tail" of the direct ionization process extends to much higher values of collected charge than expected from the peak. The angular dependence is gradual rather than "sharp" because of the width of the ionization pulse. If the critical charge is too high (as for the Micropac optocoupler), the maximum cross section at extreme angles will be lower than expected from simple geometrical arguments corresponding to the peak value of the direct ionization pulse.

## *C. Model for Angular Dependence*

The experimental results in Figures 4 and 5 show very slight energy dependence at angles below 45 º, and also show that the cross section at low incident angles is lower as the energy is decreased. This is consistent with the assumption that the contribution from proton recoils dominates the response at low angles; the lower cross section results from the reduced peak in the energy distribution of reaction products (see references 11 and 12). The reduced cross section results for moderate angles are also consistent with the energy distribution of Figure 10; if we simply translate the direct ionization component to increased energies using the cosine law, the high energy "tail" from direct ionization is still below the critical charge.

As the angle increases, the ionization "tail" begins to overlap the spectrum of recoil products, causing the cross section to increase. Assuming that the width of the ionization contribution scales with angle, it is possible to calculate the critical angle where the cross section begins to increase because of the direct component. Table 2 shows the results of that calculation for the HP 6N134 optocoupler. It is in reasonable agreement with the experimental results of Figure 4. Two second-order effects are difficult to incorporate. The first is uncertainty about the dependence of the width of the direct ionization pulse, which is due to energy straggling [13], on proton energy. The second is the fact that the cross section of the optocoupler is not exactly constant, but increases by a factor of about two as one varies the collected charge from the threshold level to levels a factor of two above threshold. Nevertheless, the results support the assumption that only the ionization component is involved in forcing the cross section above the "background" level of the proton reaction products.

Table 2. Calculated Angle for 10% Increase in Cross Section

| Proton Energy (MeV) | Charge in 50 µm Detector at Normal Incidence (fC) | Angle for 10X Increase in Cross Section (°) |
|---|---|---|
| 95 | 3.2 | - - - |
| 65 | 4 | - - - |
| 50 | 5 | 81 |
| 30 | 7.5 | 75 |
| 15 | 12 | 62 |

The aspect ratio of the photodiode structure is also important, eventually cutting off the effect of the cosine law. The effective charge collection depth must be known along with the area of the structure. For the 6N134, previous work with heavy ions showed that the effective charge collection depth was nominally 50 µm [2]. This extended collection depth is due to charge collection by diffusion. The diffusion component will increase the effective area of the photodiode beyond the measured area. With those assumptions, the aspect ratio of the 6N134 is very nearly 10:1. Therefore the angular dependence will no longer be effective for angles above approximately 85 °. This agrees with experimental observations.

The model illustrates the interplay between critical charge -- which is affected by the dimensions of the photodiode, the charge collection depth, and the gain and speed of the amplifier -- and the angle at which direct ionization becomes important. It is important to realize that although the 6N134 is commonly used in space applications, other optocouplers are manufactured with increased optical sensitivity and higher speed. Thus it is possible that some types of optocouplers may exhibit increases in cross section at much lower angles than the 6N134.

## *D. System Error Rate Calculations*

The energy spectrum of protons in a particular orbit is required to calculate the effects of the angular dependence on the upset rate, along with the upset cross section. The spectrum depends on the amount of shielding between the device and the external environment as well. However, the proton upset rate now depends on angle as well as proton energy.

The first step in this calculation was to integrate the cross section over the entire range of angles for each proton energy. The cross section is essentially flat (isotropic) for high energies. The result of that calculation (which incorporates the angle dependence indirectly, and can be used transparently in existing computer codes for error rate calculations) was to provide a revised *effective* cross section for proton upset that is energy dependent. Figure 11 shows the result, along with the result for an omnidirectional flux that does not take the angle dependence into account.

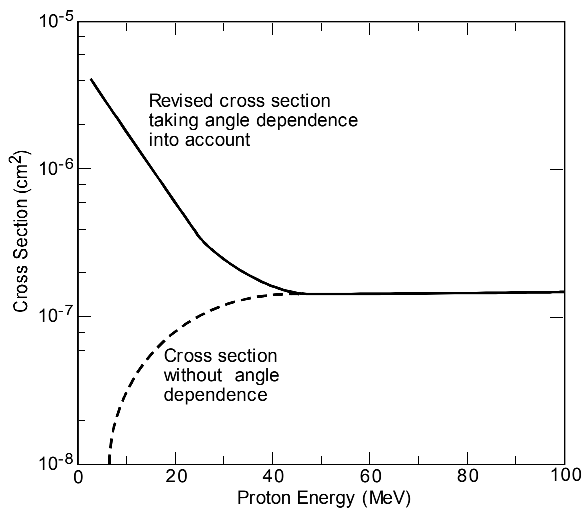



Figure 11. Effective cross section vs. proton energy taking the angle dependence of the proton upset cross section into account.

This result was then applied to a high-inclination earth orbit that is used by several NASA systems (EOS for example). The altitude is 705 km, with 98° inclination. The error rate calculation was done by integrating the effective cross section in Figure 11 over the spectrum of proton energies. Table 3 shows the results of this calculation for three different shield thicknesses. There is a significant increase in the upset rate, particularly for cases with intermediate shielding. Similar factors are expected for other earth-orbits at low to intermediate altitudes, because their proton spectra are only weakly dependent on energy for the shielding conditions in the table. The factors are likely much higher for geostationary transfer and MEO orbits, which have higher numbers of protons at low and intermediate energies than the orbit used for the calculations in Table 3 [14].

Table 3. Upset Rate Calculations for a 705 km, 98º Orbit

| Shield Thickness (mils of Al) | Upsets/Year (with angle effect) | Upsets/Year (no angle effect) | Ratio |
|---|---|---|---|
| 60 | 2,265 | 516 | 4.39 |
| 100 | 1,665 | 470 | 3.53 |
| 250 | 916 | 364 | 2.52 |

## VI. Conclusions

This paper has shown that direct ionization causes a large increase in the cross section for single-event transients in one type of high-speed optocoupler. The magnitude and the angle at which the direct ionization component affects the response increases as the proton energy decreases, which is consistent with the energy dependence of LET. The maximum increase in cross section that was observed is more than 1000 times above the cross section at normal incidence, but even larger factors may occur at lower energies. It is also possible that other optocoupler designs with higher sensitivity and/or speed may be even more sensitive, increasing the importance of the angular effect on error rate.

Error rate calculations for a common earth orbit used by NASA systems show that the angle and energy dependence of the cross section can increase the error rate by about a factor of four. Even higher factors are possible for other orbits, or for optocouplers with larger areas or aspect ratios.

A technique for measuring critical charge with laboratory alpha particle sources was demonstrated that is potentially applicable to a wide range of optocoupler technologies. The critical charge estimated in this way can be combined with simple measurements of the photodetector geometry to determine whether proton ionization is likely to be important for specific devices. This technique is potentially important as a hardness assurance tool as well as in corroborating the role of the direct ionization mechanism. It also provides a convenient way to screen devices in the laboratory before subjecting them to a costly series of proton tests at various energies and angles.

## Acknowledgement

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